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How to cite:

Slade, David; Price, Alex; Hamp, Rachael and Ramkissoon, Nisha (2018). Biosignatures in the solar system. *The Biochemist*, 40(6) pp. 6–9.

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Version: Version of Record

Link(s) to article on publisher's website:
<http://dx.doi.org/doi:10.1042/bio04006006>

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Biosignatures in the solar system

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Humanity's interest in whether or not we are alone in the universe spans generations, from Giordano Bruno's 16th century musings on other worlds and Giovanni Schiaparelli reporting seeing 'canali' in 1877 on the surface of Mars (which were thought to have been created by intelligent life) to alien invasions portrayed in today's movies. However, it is still unclear if other planetary bodies are capable of supporting life.

In the search for life there are two broad areas we look into, the requirements of life and actual signs of life. The identification of the key requirements for life enables scientists to focus life detection efforts onto planets and satellites that are considered habitable and more likely to support life. However, our ability to find life or detect signs of life is based on our understanding of life on Earth.

What does life need?

It is strongly believed that if life exists elsewhere in the solar system it will be in the form of microscopic organisms. Fortunately, all life on Earth, no matter its size, requires three key basic components:

1. Bio-essential elements – the elements required to make biomolecules for building cells, the six most important are carbon, hydrogen, nitrogen, oxygen, phosphorus and sulphur (CHNOPS or SPONCH), which microbial life can obtain from rocks and minerals.
2. A solvent – a liquid solvent is required to help facilitate the movement of bio-essential elements enabling the formation of molecules. On Earth this solvent is in the form of water, which is able to dissolve various substances, including salts and organics. Water also has a high heat capacity, it requires a lot of energy to cause it to vaporize, meaning it can provide a relatively stable environment inside cells regardless of temperature changes in the external environment.
3. Energy – energy is used for the replication, repair, growth and other cellular activities. Energy can be obtained from either chemical energy or from sunlight.

All three of these requirements need to exist at the same time along with favourable conditions (ideally, relatively low salinity, circumneutral pH and protection from harmful radiation) for a planet or satellite to be considered habitable.

Signs of life

The most obvious sign of life would be the direct observation of a living organism *in situ*, however, indisputable proof that it was not a result of terrestrial contamination would be required. Biosignatures can provide indirect evidence of past or present life. These are features or patterns that could only have been formed as a result of biological activity. They can come in the form of organic material, atmospheric gases, mineral formations, morphological features, textures or chemical changes in rocks, minerals and even fluids. To ensure that biosignatures could only have been formed by biological activity, it is important to conduct controlled experiments comparing biological and non-biological systems.

Where to start?

Liquid water is by far the most difficult of the key requirements to find in the solar system, as it requires a very narrow set of physical conditions for its existence. Therefore, missions searching for life in the solar system have focused on bodies that show signs of water activity, past or present. Hence, NASA's stated strategy, 'Follow the Water'.

First stop, Mars

The Mariner 4 flyby in 1965 gave us the first close encounter of the Martian surface. Since then over 20 missions have been sent to explore the planet. These missions have provided insight into the chemistry and geology of surface materials, and revealed extensive valley networks, channels and even a potential shoreline, apparently carved by fluid motion across the planet's surface. Decades of research have placed the vast majority of these features at ages of more than 3.7 billion years, during an era referred to as the Noachian. There is compelling evidence that Noachian Mars was a much more geologically dynamic place, with widespread volcanism feeding a dense, anoxic atmosphere which would have warmed the planet. This combination of higher pressures and temperatures is thought to have allowed long-lived riverine and lake environments, or even a hydrological cycle, to persist at the surface. This indicates Mars could have been much more habitable and potentially support life during this time, but how would we know and does life still exist there day?

Evidence of Martian organic molecules

Today, the Martian surface is dry, arid, oxidizing, with no permanent liquid water and the intense radiation makes it unlikely life could exist there. Despite this, NASA's Curiosity rover has found evidence of organic molecules within the Martian regolith. However, the exact origin of these organics is unclear and could also have been delivered to the surface by meteorite impacts. The upcoming ESA ExoMars 2020 rover mission will be the first to sample the subsurface, drilling to a maximum depth of 2 m to search for subsurface organic molecules where they are more likely to be protected from radiation and remain intact. Today, the deep subsurface could be a refuge for contemporary life, where conditions would be more conducive to sustain liquid water.

Atmospheric biosignatures

The thin atmosphere primarily consists of carbon dioxide (~95%), and a host of trace gases, particularly methane, which might indicate the presence of life. The detection of methane has led to the question of where it comes from. On Earth more than half of all atmospheric methane is produced by microorganisms, but there are also geological processes capable of producing methane. Luckily, it is possible to determine if this atmospheric methane has been formed by biological or non-biological processes, by looking into the carbon isotopes that make up methane (biological methane is enriched in carbon 12 isotopes

relative to non-biological methane). The ExoMars Trace Gas Orbiter (TGO), which is currently orbiting Mars, will 'sniff' the trace gases present in the atmosphere helping to determine the processes involved in forming methane.

What might have lurked on early Mars?

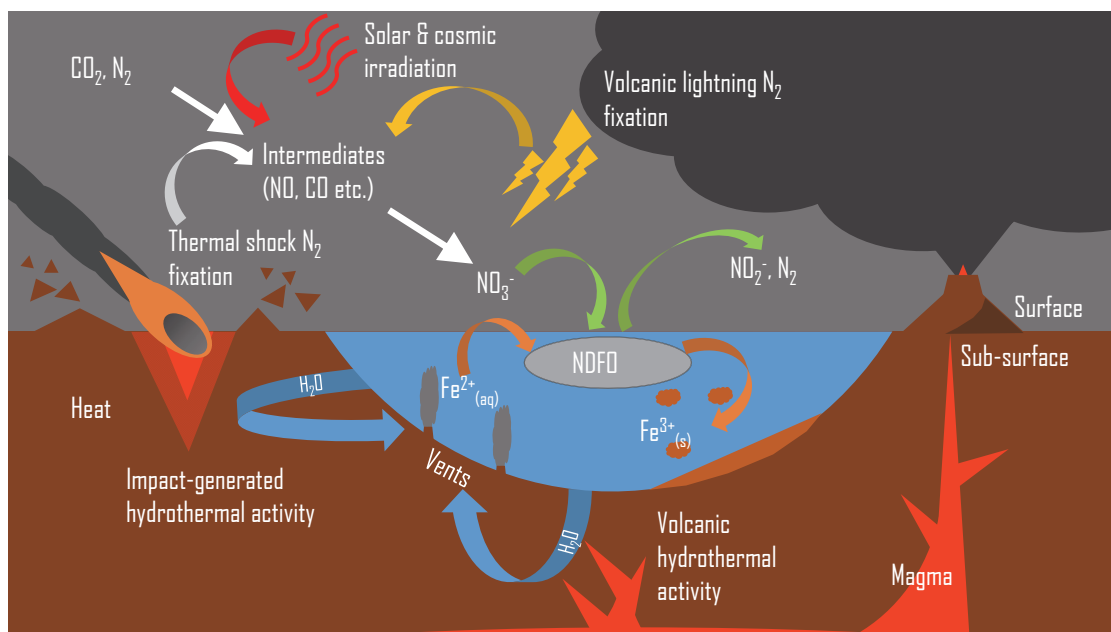
The Martian surface today may be pretty inhospitable but that was not necessarily always the case. From the earliest missions to the red planet, we have had hints that this desertified rock may once have been a much more habitable environment. Spectrometers onboard spacecraft such as NASA's Mars Reconnaissance Orbiter and ESA's Mars Express, have studied the chemistry and mineralogy of the surface from afar, while surface rovers such as Curiosity have probed Martian rocks directly. From this, we know that Mars holds abundant opportunities for energy metabolism, inorganic electron donors in reduced iron and sulphur compounds together with terminal electron acceptors such as nitrates, perchlorates, sulphates and oxidized iron species provide feasible redox pairs.

The abundance of inorganic energy sources focuses early Martian astrobiology on lithotrophic metabolisms, whereby microbes directly obtain energy from rocks and minerals. Those which have been extensively considered include sulphate reducers, acidophilic iron oxidizers and iron reducers. Biological iron cycling is of prime interest due to the high iron content of Martian geology, which is roughly double that of the Earth. However, acidophilic iron oxidizers are aerobic microorganisms, which poses a problem when there is no strong evidence for high levels of free oxygen in the early atmosphere.

One alternative being investigated is nitrate-dependent iron oxidation, which exists in anoxic sediments and waters on Earth. These microbes couple nitrate reduction or denitrification to the oxidation of reduced iron under near-neutral pH conditions. We know that conditions such as these existed at Gale Crater in the distant past, thanks to investigation of ancient lake sediments by Curiosity, and so hypothetical biogeochemical cycles based on this metabolism have already been proposed (Figure 1).

The geochemical information sent back from Mars, makes it possible to recreate early Martian environments, under controlled laboratory conditions, to determine if these microbes could have grown and thrived there. Experiments of this kind may also reveal novel biosignatures. Under exceedingly high dissolved iron concentrations, the iron oxides produced by these microbes can precipitate in the cell wall and entomb them. These rusty shells could have been preserved in sedimentary environments, providing us with morphological biosignatures to search for today.

Figure 1. Potential energy sources and cycles for nitrate-dependent iron-oxidizing (NDFO) microbes on early Mars (Price, A., Pearson, V.K., Schwenzer, S.P., Miot, J. and Olsson-Francis, K. (2018) Nitrate dependent iron oxidation: a potential Mars metabolism. *Frontiers in Microbiology* 9, 513)



New places to explore

The focus of astrobiology has recently expanded from Mars to include the icy moons of Jupiter and Saturn. This is predominantly due to the recent discovery of subsurface oceans on Enceladus and Europa, meaning large supplies of liquid water. While both moons hold great astrobiological potential, the Cassini spacecraft has provided us with a wealth of knowledge that can assist in determining if life could or does exist on Enceladus in particular.

What makes Enceladus so interesting?

Until recently little was known about Enceladus, besides it having the highest reflectivity of any natural satellite, which implies the ice crust is nearly 100% pure water ice. The NASA Cassini mission has since studied the moon in detail and sampled material emanating from plumes being ejected from the southern polar region. Cassini discovered that Enceladus is comprised of an outer icy layer, a global subsurface ocean and then a rocky interior (Figure 2). However, by far the most exciting recent discovery is that Enceladus could potentially harbour life.

Why do we think Enceladus could be a habitable environment?

Of the three key requirements for life mentioned, Enceladus appears to possess a full house. Beneath its icy exterior lies a global subsurface ocean. The detection of water ice, salts and ammonia within the plumes has helped prove a source of present liquid water.

These plumes have been studied by ion and neutral mass spectrometry, which detected some of the bio-essential elements (carbon, nitrogen and hydrogen). These elements have been detected in the form of molecular hydrogen and nitrogen, carbon dioxide, methane, ammonia and both short chain aliphatic hydrocarbons and macromolecular organics. This suggests the plausible existence of methanogens, nitrogen-fixing bacteria and/or ammonia-oxidizing bacteria within the subsurface ocean.

Finally, Cassini measured a high heat flux on the south polar region, implying some chemical or physical process occurring beneath the icy exterior providing an internal source of energy. The detection of molecular hydrogen within the plumes also suggests a high probability of ongoing hydrothermal activity occurring at a rocky core-ocean interface, which is supported by the general chemistry of the plumes that is comparable to hydrothermal vents on Earth. These have been suggested as the site for a hypothetical origin of life on Enceladus.

How are we studying Enceladus and potential habitability?

Using data provided by Cassini helps to constrain physical and chemical parameters, allowing us to simulate the subsurface environment in a laboratory. These simulated environments will help answer questions of theoretical habitability, establishing the chemical species present, potential redox gradients and potential growth of microbial species.

Summary

Ongoing investigation of the modern Martian environment, recreations of early aqueous conditions and subsurface environments of the icy moons are not only helping to advance our understanding of the limits and requirements of life, but also support ongoing and future missions through identification of potential biosignatures.

Whether we are looking for active or ancient life, on Mars, an icy moon or any other celestial body, life leaves behind clues to find. Life as we know it requires a number of prerequisites and by using this set of known parameters, as well as knowledge of biological processes on Earth, we can approach this challenge in a logical and scientific manner. Searching for the clues to find life outside of our own biosphere is both exciting, engaging and will hopefully answer one of the biggest questions facing humanity. ■



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Alex Price is a microbiology PhD student in The Open University astrobiology group. He is researching potential microbial metabolisms and biosignatures in early Mars conditions, specifically focusing on mechanisms of anaerobic microbial iron oxidation and survival under simulated

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Rachael Hamp is a chemistry PhD student in The Open University astrobiology group. Her research is studying the water-rock interactions on Enceladus, focusing on the carbon cycling within the subsurface environment. Email: rachael.hamp@open.ac.uk



Nisha Ramkissoon is a postdoctoral research associate in the astrobiology group at The Open University. Her current research focuses on the identification of biosignatures that may occur as a result of microbial activity on Mars and the icy moons. In addition to this she also examines mineralogical changes

that can arise in the high-pressure and temperature environments after hypervelocity impact. Email: nisha.ramkissoon@open.ac.uk

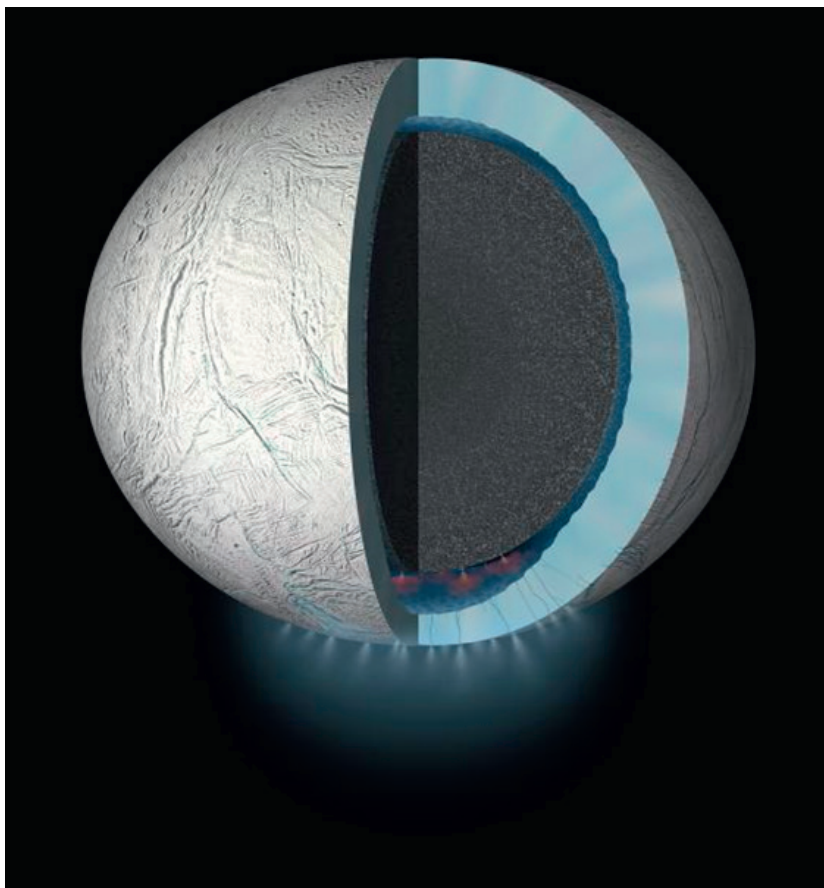


Figure2. Artists graphical representation of the structure of Enceladus.

Image Credit: NASA/JPL-Caltech

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